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EFFECT OF LOW AIR VELOCITIES ON THERMAL HOMEOSTASIS AND COMFORT DURING EXERCISE AT SPACE STATION OPERATIONAL TEMPERATURE AND HUMIDITY

Final Report

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ABSTRACT

This study investigated the effectiveness of different low air velocities in maintaining thermal comfort and homeostasis during exercise at space station operational temperature and humidity. Five male subjects exercised on a treadmill for successive ten minute periods at 60, 71 and 83% of maximum oxygen consumption at each of four air velocities, 30, 50, 80 and 120 ft/min, at 22°C and 62% relative humidity. No consistent trends or statistically significant differences between air velocities were found in body weight loss, sweat accumulation, or changes in rectal, skin and body temperatures. Occurrence of the smallest body weight loss at 120 ft/min, the largest sweat accumulation at 30 ft/min, and the smallest rise in rectal temperature and the greatest drop in skin temperature at 120 ft/min all suggested more efficient evaporative cooling at the highest velocity. Heat storage at all velocities was evidenced by increased rectal and body temperatures; skin temperatures declined or increased only slightly. Body and rectal temperature increases corresponded with increased perception of warmth and slight thermal discomfort as exercise progressed. At all air velocities, mean thermal perception never exceeded "warm" and mean discomfort, greatest at 30 ft/min, was categorized at worst as "uncomfortable"; sensation of thermal neutrality and comfort returned rapidly after cessation of exercise. Suggestions for further elucidation of the effects of low air velocities on thermal comfort and homeostasis include larger numbers of subjects, more extensive skin temperature measurements and more rigorous analysis of the data from this study.

INTRODUCTION

An exercise regimen is being developed to help counter musculoskeletal degeneration during sustained space flight. The thermal environment during this exercise must be sufficient to avoid extensive heat storage and should suffice to maintain thermal comfort, including minimal accumulation of unevaporated sweat. It is not known whether specified space station habitat and exercise station air velocities (15-40 and 80 ft/min), temperatures (65-80°F, 18.5-26.7°C) and dew points (40-60°F, 4.5 - 15.5°C) will accomplish these objectives. The purpose of this study was to investigate the effect of similar air velocities on heat storage and comfort of subjects exercising according to a space station protocol, at space station operational temperature and humidity.

METHODS

Five male subjects exercised on a treadmill at each of four air velocities at approximately 22°C and 62% relative humidity, the mid-range of selectable temperature and near the upper limit of allowable humidity. Each subject exercised at the same time of day over a period of two weeks, July 25 through August 4, 1989. Except for tests on two successive days for two subjects, a minimum of one day rest intervened between successive tests for each subject. The sequence of air velocities was randomized for each subject. All subjects had undergone a stress test within the past year and gave their informed consent to testing, approved by the Johnson Space Center Human Research Policy and Procedures Committee. Subject characteristics at the time of the stress tests are given in table 1.

Tests were conducted in an environmental chamber 1.8x2.7x2.5m high. An open plastic grid 16cm beneath the ceiling diffused light from two 80 watt fluorescent tubes mounted on the ceiling. Environmental temperature was calculated as the mean of air and wall temperatures measured immediately before and after each test. Relative humidity was similarly determined from psychrometric data. Extremes of wall temperature for all tests were 21.4-23.0°, of air temperature 21.0-23.1°, of relative humidity 54-66.5%. Table 2 presents mean temperature and humidity conditions during testing at the different air velocities.

Controlled air flow was provided by two 56x56cm fans on shelves 1.2m behind the exercising subject. Fan air flow was turbulent but primarily parallel to the treadmill. Fan speeds were adjusted so as to provide, in combination with

TABLE 1.- PHYSICAL CHARACTERISTICS OF SUBJECTS

Subject	Weight kg	Height cm	Body Fat %	Age	Maximum oxygen consumption ml/kg/min
1	95.9	184	29	33	45.9
2	67.2	172	9	27	49.1
3	77.8	165	16	27	38.5
4	76.3	180	12	40	38.3
5	75.4	176	24	49	37.0

TABLE 2.- MEAN TEMPERATURE (^{o}C) AND RELATIVE HUMIDITY

Air velocity	Temperature	Humidity
30	21.9	62.4
50	22.2	62.7
80	22.3	61.0
120	22.3	60.4
Mean	22.2	61.6

uncontrolled air flow associated with the temperature and humidity control system, the air flows used during testing.

Nominal air velocities used were the means of at least two replicates of air velocities measured at twelve points in a vertical plane perpendicular to the treadmill and at the approximate location of the exercising subjects. Four measurement points each were used at 0.5, 1.0 and 1.5m above the treadmill. At each point, measured air velocity was taken as the mean of the mid-points of five ten-second ranges of air velocity. Mean air velocities at the three levels are presented in table 3.

TABLE 3.- NOMINAL AND MEASURED AIR VELOCITIES (FT/MIN)

Nominal velocity	30	50	80	120
Meters above treadmill:				
0.5	49	50	93	94
1.0	32	61	81	183
1.5	16	45	67	88
Mean	32	52	80	122
Standard deviation	16	8	13	53

The suggested space station exercise schedule specifies successive ten minute periods at 65, 75 and 85% maximum oxygen consumption. Treadmill speeds and grades needed to achieve these oxygen consumptions for each subject were estimated using the chart and formula of Givoni and Goldman (1971). Small adjustments were made after each subject's first test to more closely approximate targeted values. The range of speeds and grades used was 5.6-6.6km/hr and 5-15%.

Before each test, thermistor probes were attached with porous paper tape to the mid-sternum, anterior left thigh and dorsal left hand of the subject, a rectal thermistor was inserted to 10cm, and EKG electrodes and transmitter were attached; total mass of this apparatus was approximately 430gm. The nude subject was then weighed to the nearest 5gm on an electronic platform balance before donning preweighed shorts, socks and shoes. Within five minutes after completing exercise, clothing and a towel used to remove perspiration after exercise were placed in a plastic bag and nude weight was again determined. Body weight loss was determined as the difference of these two weights; unevaporated sweat accumulation was estimated as the difference in garment and towel weight before and after exercise.

After the first weighing, fans were turned on and the subject stood at rest on the treadmill for 15 minutes in order to establish thermal equilibrium. At the beginning of this period, the beginning of exercise, and at each five minute interval thereafter during exercise and a subsequent 15 minute recovery period, rectal and the three skin temperatures were recorded. Mean skin and body temperatures were computed according to equations modified from Berenson and Robertson (1973):

$$T_{skin}=0.53T_{thigh}+0.33T_{chest}+0.14T_{hand};$$

$$T_{body}=0.67T_{rectal}+0.33T_{skin}.$$

At the same time intervals, subjects categorized perception of temperature and thermal comfort according to temperature and discomfort scales described by Gagge et al. (1967) and illustrated in table 4. Scales were posted in front of the treadmill to facilitate subject response.

During the initial equilibrium period and at the mid-point of each exercise level, oxygen consumption and carbon dioxide production were measured by timed collection of

TABLE 4.- TEMPERATURE SENSATION AND THERMAL COMFORT SCALES

Temperature:		Comfort:	
-3	cold	0	comfortable
-2	cool	1	slightly uncomfortable
-1	slightly cool	2	uncomfortable
0	neutral	3	very uncomfortable
+1	slightly warm	4	intolerable
+2	warm		
+3	hot		

expired gas samples and analysis of gas composition by a mass spectrometer.

RESULTS

Table 5 presents mean percentages of maximum oxygen consumption during the three ten minute periods of exercise at each air velocity. The percentage in each case was lower than the targeted values of 65, 75 and 85%. Analysis of variance (ANOVA) within exercise periods revealed no significant differences between the different air velocities.

TABLE 5.- MEAN PERCENTAGE OF MAXIMUM OXYGEN CONSUMPTION DURING SUCCESSIVE EXERCISE PERIODS ( )=S.D.

Air velocity ft/min	Period First	Second	Third
30	59 (6)	73 (6)	81 (11)
50	60 (6)	71 (6)	82 (10)
80	62 (7)	72 (9)	81 (7)
120	60 (6)	71 (10)	83 (11)

Body weight loss was least at 120 ft/min and sweat recovered was greatest at 30 ft/min (table 6). ANOVA indicated no significant differences between air velocities for any of these parameters.

Figures 1 and 2 show that rectal and body temperatures both rose gradually through the exercise period and declined during the recovery period. The decline in rectal temperature was more gradual than its rise and more immediate and consistent than the decline in body temperature. Air velocity had little effect on the change in rectal temperature at 30 minutes, nor any consistent effect on body temperature. ANOVA indicated no significant differences between air velocities in mean body or rectal

TABLE 6.- MEAN ABSOLUTE AND PERCENTAGE BODY WEIGHT LOSSES, ABSOLUTE WEIGHT OF RECOVERED SWEAT AND WEIGHT OF RECOVERED SWEAT AS PERCENTAGE OF BODY WEIGHT LOSS ( )=S.D.

Air velocity	Weight loss		Sweat recovered	
ft/min	gm	percent	gm	percent
30	425 (213)	0.5 (0.2)	85 (95)	16.2 (10.5)
50	421 (174)	0.5 (0.2)	68 (75)	13.5 (9.5)
80	442 (158)	0.6 (0.1)	63 (69)	12.1 (9.6)
120	356 (229)	0.4 (0.2)	64 (72)	14.8 (7.9)

temperature changes at 30 minutes.

All skin temperatures dropped initially and then rose slightly (figure 3). At 80 and 50 ft/min, skin temperature continued to rise through the exercise period, at 30 ft/min it oscillated, and at 120 ft/min it declined until the end of the exercise. At the end of the exercise period, the skin temperatures at 50 and 80 ft/min were approximately the same as at the beginning of the period; the greatest change was at 120 ft/min, slightly greater than that at 30 ft/min. Differences at 30 minutes were not statistically significant.

During recovery, skin temperatures first rose then declined precipitously at all air velocities except 80 ft/min, in which case the opposite occurred. At the end of the recovery period, the greatest change from the start of the exercise was at 120 ft/min and the least at 80 ft/min.

Figure 4 indicates that mean temperature perception at the start of exercise was slightly cool at 80 and 120 ft/min and near neutral at 30 and 50 ft/min. Ranking of perceived temperature rose until the end of exercise, when subjects felt warm at 80 ft/min and between slightly warm and warm at other velocities. Feeling of warmth decreased rapidly at the beginning of the recovery period and thereafter approximated starting values.

Subjects at 120 ft/min were slightly less comfortable than at other velocities at the beginning of exercise (figure 5). Mean discomfort level at 30 ft/min was almost a whole category above that at other velocities at 25 minutes. At 30 minutes, subjects at 30 ft/min gave the highest discomfort ranking, and subjects at 120 ft/min were the most comfortable. After exercise, comfort level at all velocities rapidly returned to "comfortable".

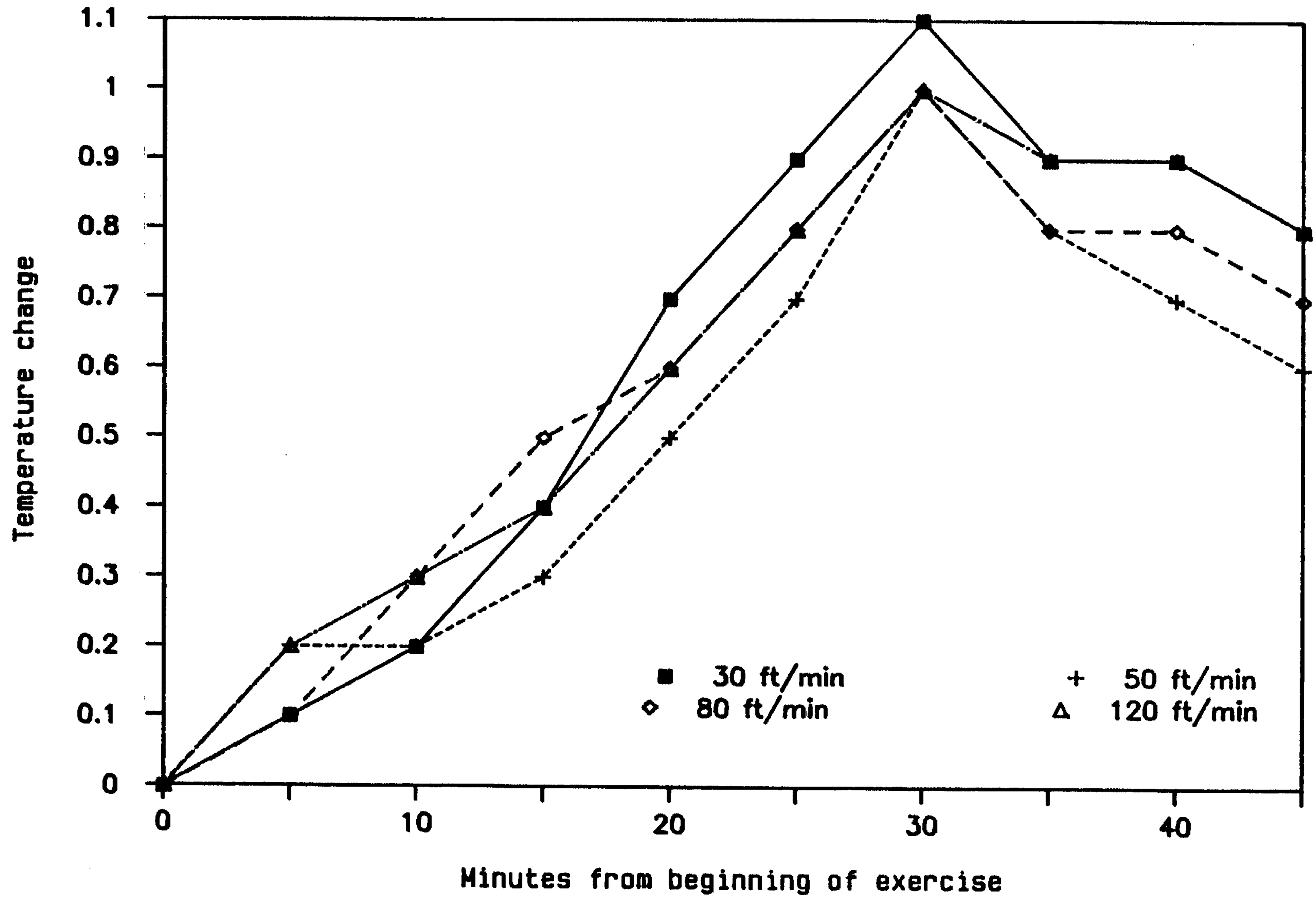

Figure 1.— Change in rectal temperature during and after 30 minute exercise at different air velocities.

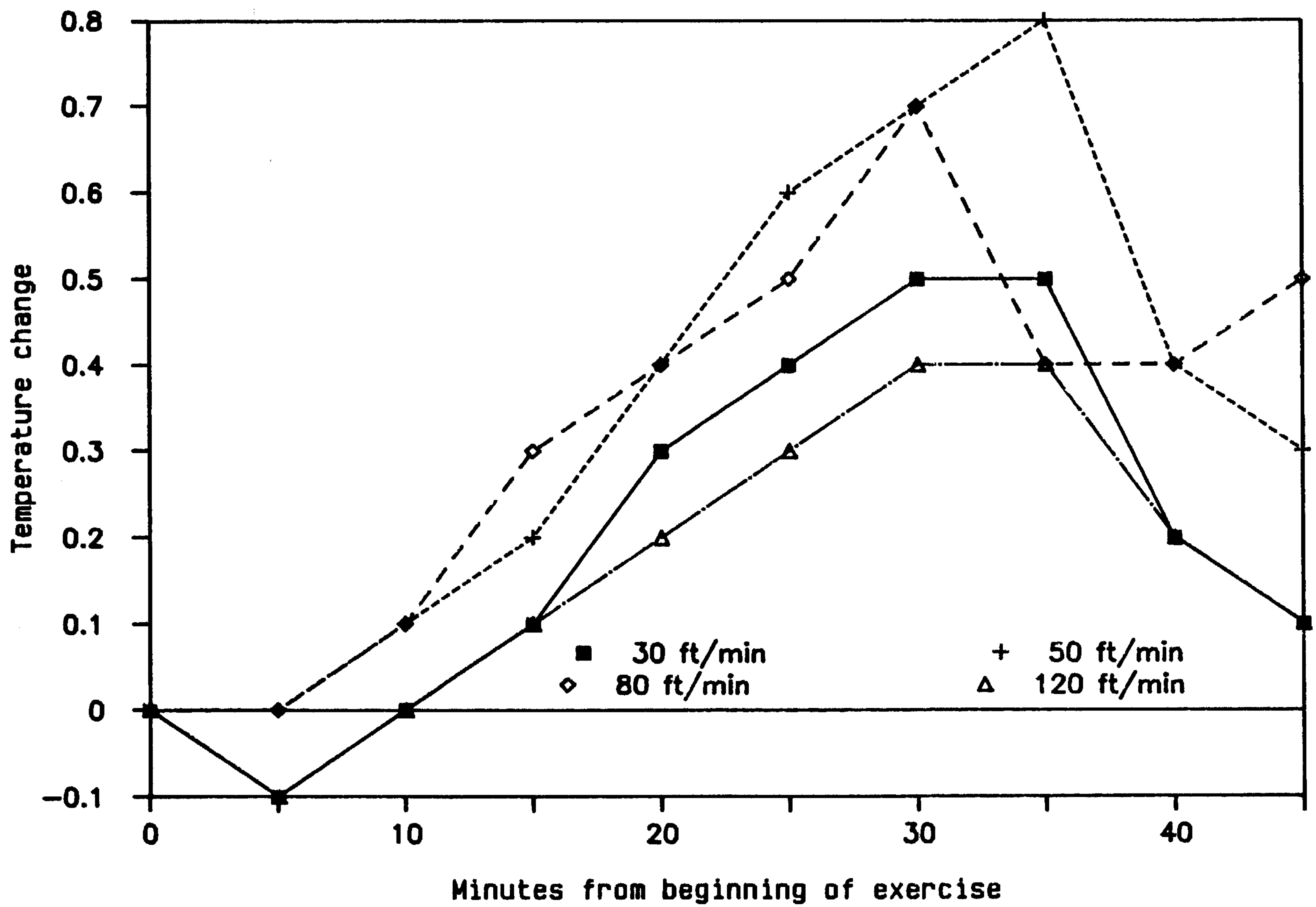

Figure 2.– Change in body temperature during and after 30 minute exercise at different air velocities.

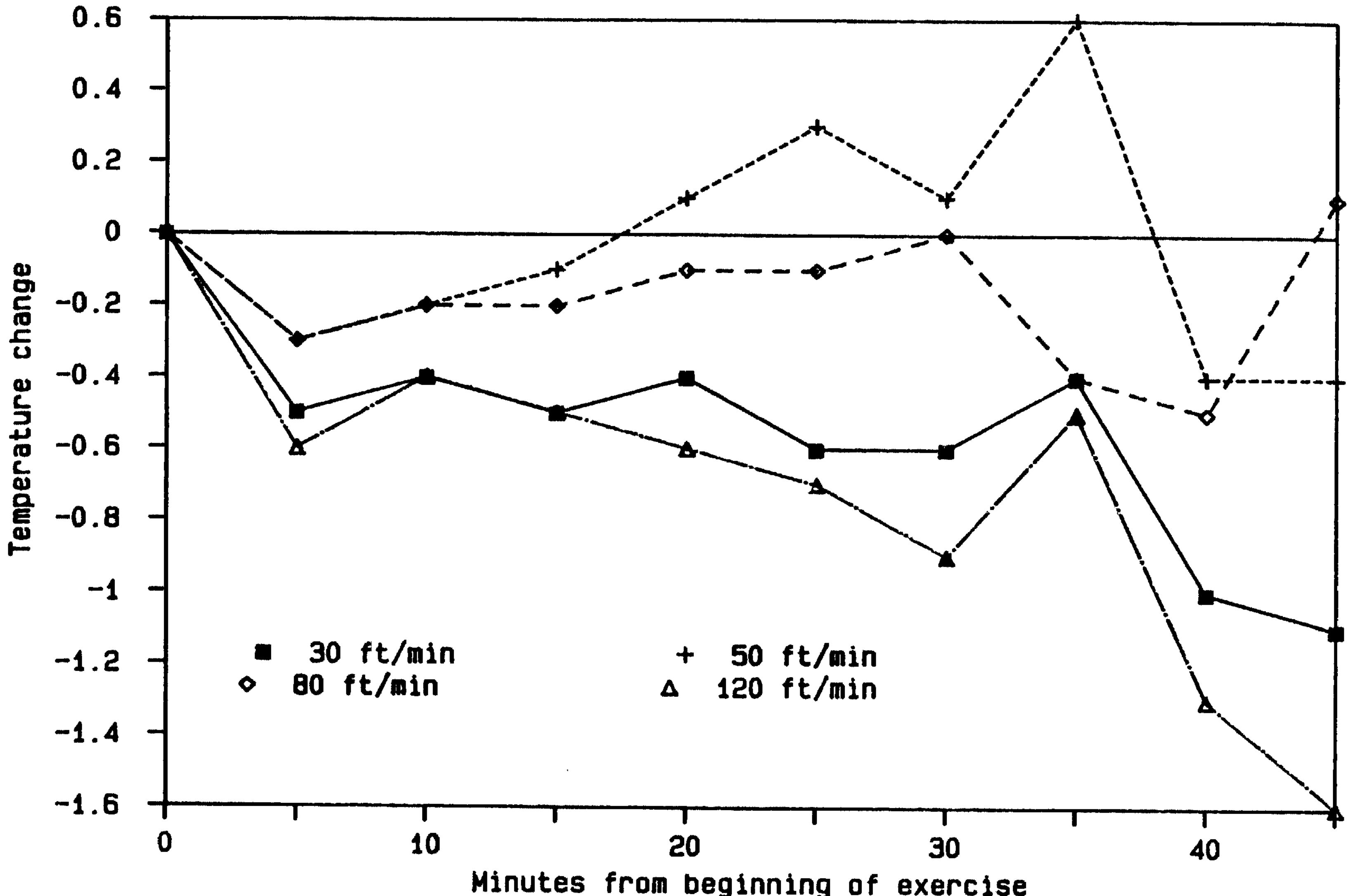

Figure 3.– Change in skin temperature during and after 30 minute exercise at different air velocities.

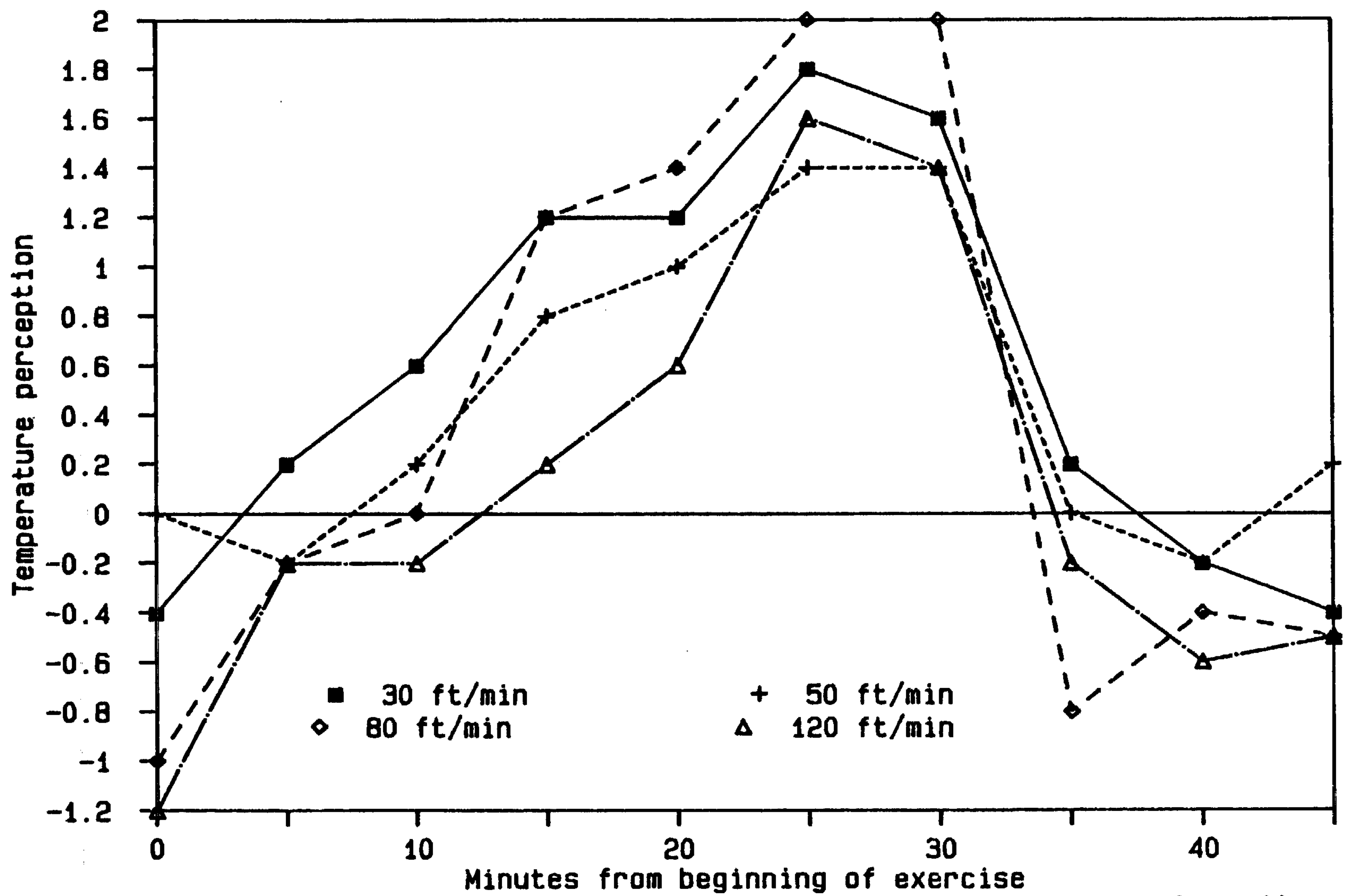

Figure 4.– Mean temperature perception during and after 30 minute exercise at different air velocities.

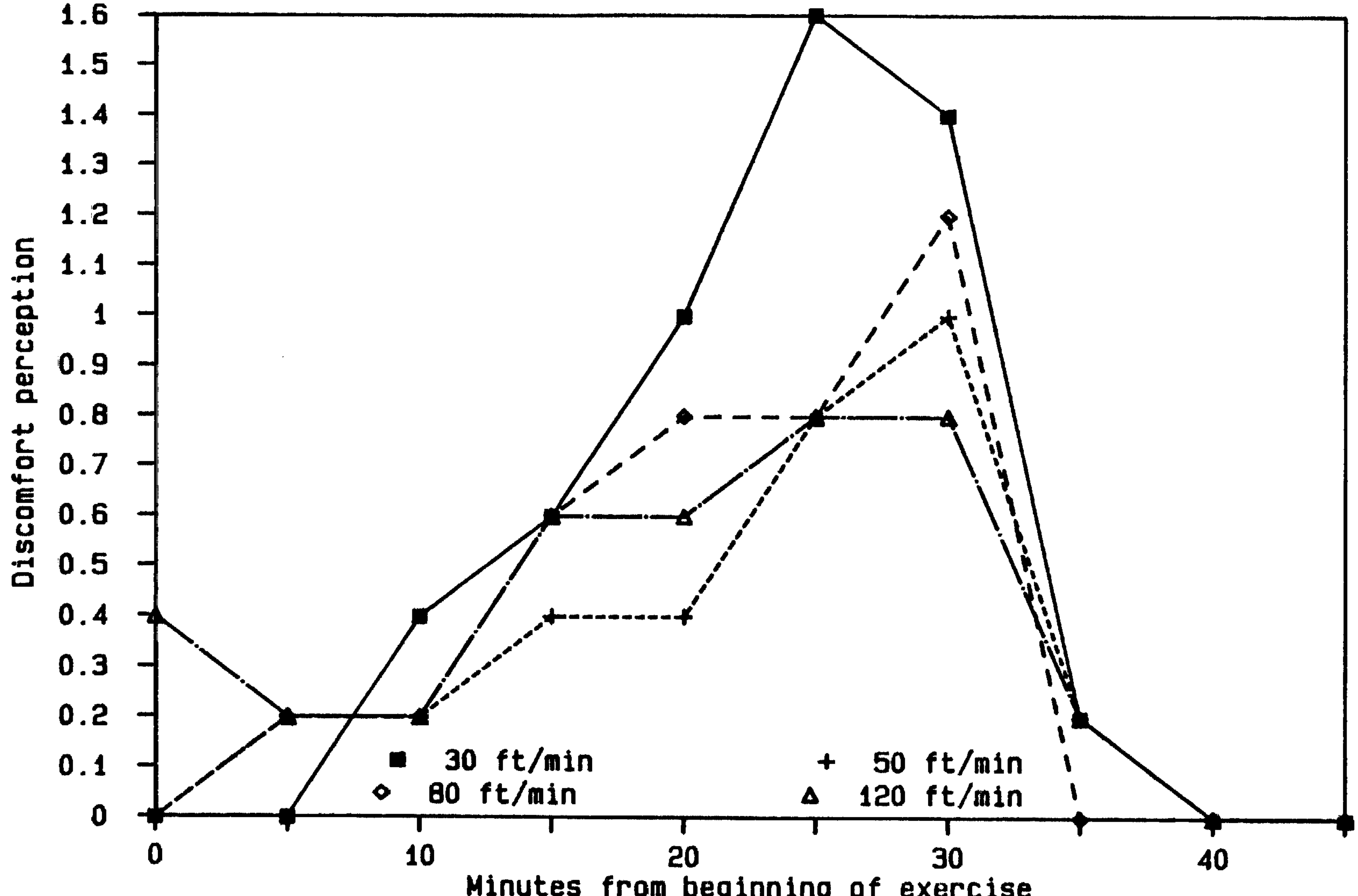

Figure 5.– Mean comfort perception during and after 30 minute exercise at different air velocities.

DISCUSSION

These results suggest little difference in the contribution of the studied air velocities to thermal homeostasis and comfort. No statistically significant effects of air velocity were observed, nor were there consistent trends in the observed parameters.

That mean energy expenditures were less than planned suggests the desirability of further study using exercise levels more closely resembling the space station protocol. Nevertheless, their similarity at the four velocities studied validates comparisons of other measured parameters.

That the smallest body weight loss occurred at 120 ft/min might be due to this highest velocity fostering more efficient evaporative cooling. This suggestion is strengthened by the greatest accumulation of sweat at the lowest velocity. More thorough analysis of these weights relative to factors such as surface area, energy expenditure and insensible evaporation may be useful.

Increases in rectal and body temperatures indicated heat storage at all air velocities. That increase in body temperature in all cases was smaller than rectal increase is explained by smaller increases or declines in skin temperature, probably the effect of evaporative cooling. That the greatest increase in rectal temperature occurred at the lowest air velocity is a reasonable corollary of reduced evaporative cooling, but a further, unfulfilled corollary would be a smaller decline in skin temperature and larger increase in body temperature than at the intermediate velocities.

Greater evaporative cooling similarly would explain the smallest rise in body temperature and greatest drop in skin temperature occurring at 120 ft/min. This conclusion is weakened by the second greatest drop in skin temperature occurring at the lowest air velocity and by only small changes at intermediate velocities.

During the post-exercise period, rectal temperatures declined more consistently than body temperatures and skin temperatures were erratic. This may reflect rectal temperature being affected more by activity and skin temperature by environment. The primary purpose of this period was to assure recovery of homeostasis; no effort was made to control the posture or location of subjects in relation to air flow. Environmental variability during this period might have contributed to variable skin temperatures. Temperature changes might have been more informative if this variability had been reduced.

Subjective sensation of being cooler before and after exercise at the higher velocities than at the lower velocities can be explained by greater convective cooling and post-exercise evaporative cooling. Lower comfort at the highest velocity than at lower velocities at the beginning of exercise probably was associated with this perception of coolness.

During the later part of the exercise period, greater discomfort was perceived at 30 ft/min than at higher velocities. A possible explanation of lesser convective and evaporative cooling is not supported by changes in measured temperatures. Greater skin wettedness as a possible explanation is corroborated by the greatest accumulation of sweat at this velocity. Decreased sensation of air movement is another possible cause.

Increased perception of warmth and slightly decreased comfort with increasing activity at all air velocities corresponds with increases in body and rectal temperatures. It is notable that at all these velocities the mean thermal sensation never exceeded warm, mean discomfort at worst was categorized between uncomfortable and slightly so, and that post-exposure perception rapidly returned to near thermal neutrality and comfort.

Although this study has revealed little difference in the effectiveness of different low air velocities under the conditions of the study, these data should be analyzed more rigorously. Perhaps also the study should be repeated under more precisely controlled conditions and using more powerful measures to either validate its results or otherwise elucidate the effects of different air velocities. In addition to suggestions made above, air flow should be more uniformly controlled or at least more completely characterized. Temperature data might be more informative if skin temperatures were measured at a larger number of sites, especially on the dorsal surface most directly affected by air flow in this study. The use of larger numbers of subjects might also help to overcome the effects of large individual differences in response to the test protocol.

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